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Development of a preamplifier for 1 to 1.7GHz with a noise figure of 0.4dB

This article is a revised and expanded version of a lecture given at the 2012 VHF meeting in Bensheim. It shows the current state of development of low noise MMIC amplifiers and a sample demonstrating the procedure for a successful design. Measurements of the prototype should confirm the design and simulations.

1. Overview

The development of high quality integrated microwave amplifier modules (MMICs) is constantly in flux, leading to better performance. Therefore it is interesting to build such an LNA because of the following benefits:

- Input and output are optimised for a 50Ω system
- The noise figures have fallen to under 0.5dB in a 50Ω system at higher frequencies (e.g. above 500MHz)
- A single device achieves approximately 20dB gain up to 2GHz.
- Little external circuitry necessary.

The sentence "No roses without thorns" applies here. You should know the problems because you can only achieve these values when you solve a whole range of tasks:

- These MMICs are tiny SMD components without connecting feet. A die is used with the dimensions of 2mm x 2mm and with 4 connections on two opposite edges (Pads) plus ground.
- The common ground of the chip is often not fed to the edge of the package but in the middle of the underside
- The layout design requires very high accuracy (tracks and connection pads on the IC are typically 0.2mm with a maximum width of 0.5mm)
- The additional SMD components for the external circuit should be 0603 size (1.25 x 0.75mm) as far as possible

The cutoff frequencies of the components are so high that the stability below 1GHz and unconditionally up to 10GHz must be controlled. The operating point must be very carefully stabilised due to the high currents (often over 50mA per IC) and the supply voltages decoupled even more careful and for extremely broadband. The thickness of the board was reduced, for all applications due to this extended frequency range, to 0.25mm to prevent undesirable signal modes on the strip lines. This means that many vias are

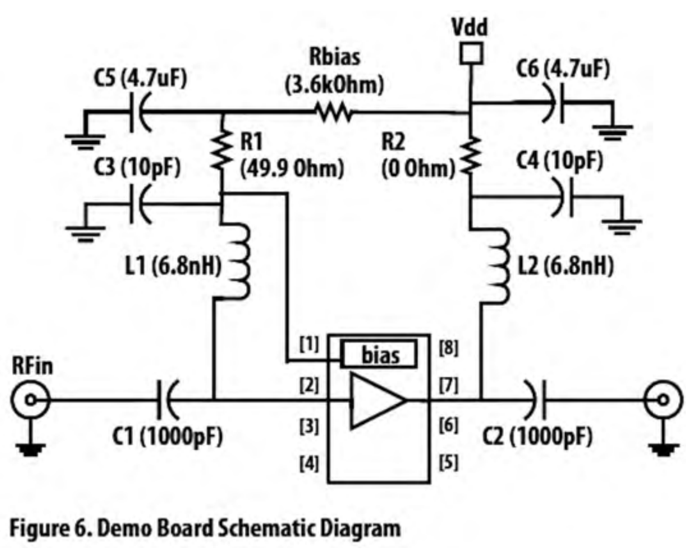

Fig 1: This circuit is used as a pattern in the data sheet and two application notes; It is the starting point for my own development.

necessary so it cannot be made manually with silver plated tubular rivets.

This project is for use in the 23 cm band (approximately 1300MHz) and intended to receive METEOSAT at 1691MHz. The following data was used to trawl the Internet for an MMIC suitable for development:

- Noise figure: maximum 0.4dB
- Amplification (S21) approximately 20dB
- Absolute stability (k greater than 1 up to 10GHz)

The choice was Agilent Avago, whose sourcing proved absolutely no problem (die components took one week to arrive after ordering online at Mouser.com) and the price (€80 for 25 pieces) for the "MGA 635P8" was acceptable.

2.

The development of the circuit

The starting point was the data sheet for the MMIC together with the downloaded S parameters and two application notes provided by the manufacturer for 2500MHz and 3500MHz [1] [2] [3]. The same basic amplifier circuit and the same PCB layout are used in all cases. Only the component values are adjusted to the different frequency ranges. Fig 1 shows this circuit and it is not hard to understand:

- It uses a supply voltage of VDD = +5V
- Inside the MMIC package is a GaAs pHEMT Cascode amplifier, as well as a bias circuit.
- The operating point is set to the desired 55mA using pin 1 to connect a resistor (3.6kΩ = R_{bias}) to the bias circuit and the generated bias is connected to the gate of the first pHEMT on pin 2 through L1 = 6.8nH.
- The other inductor (L2 = 6.8nH) provides the load resistance of the second stage.

A major problem of the HEMT components is stability at low frequencies, they tend to oscillate. A simple trick helps to deal with this: with decreasing frequency

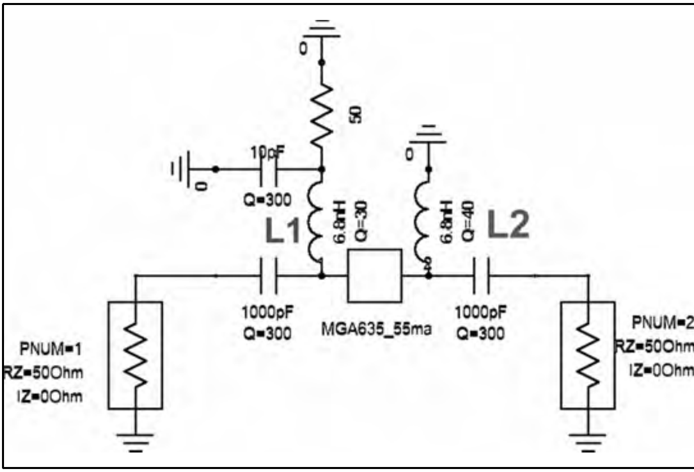

Fig 2: The circuit from Fig 1 prepared for simulation with ANSOFT Designer SV.

the additional resistor R1 of about 50Ω is introduced at the input pin 2 that effectively prevents such an oscillation.

Explanation:

The reactance of L1 (6.8nH) decreases with decreasing frequency but the reactance of C3 (10pF) increases. So at some frequency only R1 is active on the input pin.

In addition the very small inductance L2 6.8nH as a load resistance for the second stage reduces amplification at lower frequencies down to zero. The resistor R2 also shown in the circuit with a value of zero ohm was ignored.

Before the development began this circuit was investigated with ANSOFT Designer SV, Fig 2 shows the created simulation diagram.

First, the noise figure in dB was simulated and at the same time the influence of the quality of L1 = 6.8nH was determined (see Fig 3). In both cases studied the NF remains below 0.6dB. However, the noise figure still needs to be reduced for our purposes in the desired frequency range from 1.3 to 1.7GHz to meet the requirements.

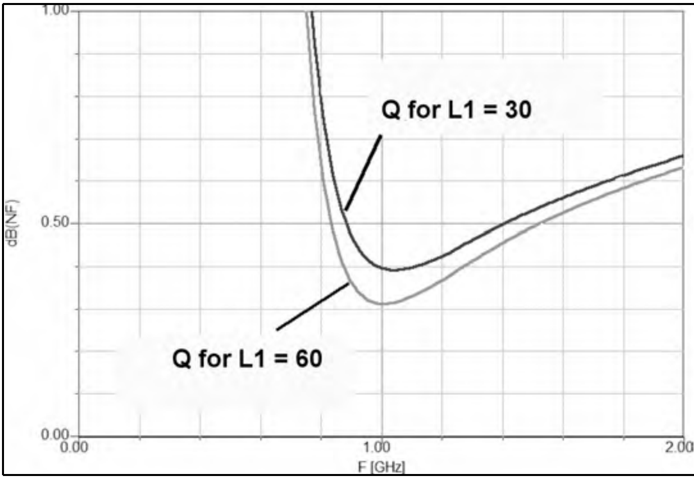

Fig 3: The noise figure achieved from the circuit in Fig 2 is unsatisfactory and depends heavily on the quality factor Q of the choke L1 = 6.8nH.

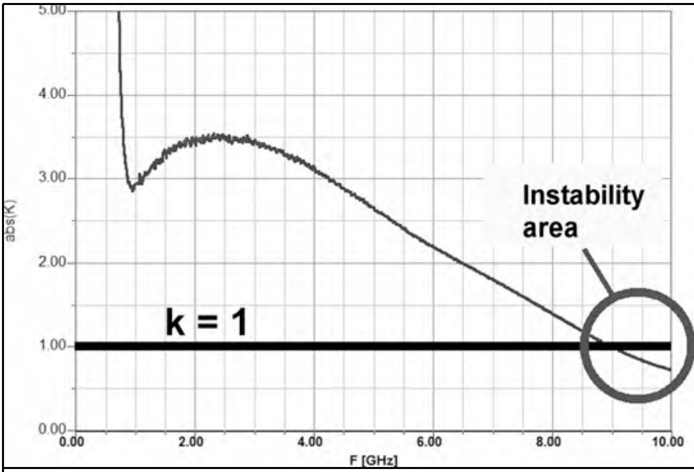

Fig 4: Because the developer was not carefully enough, this circuit will oscillate.

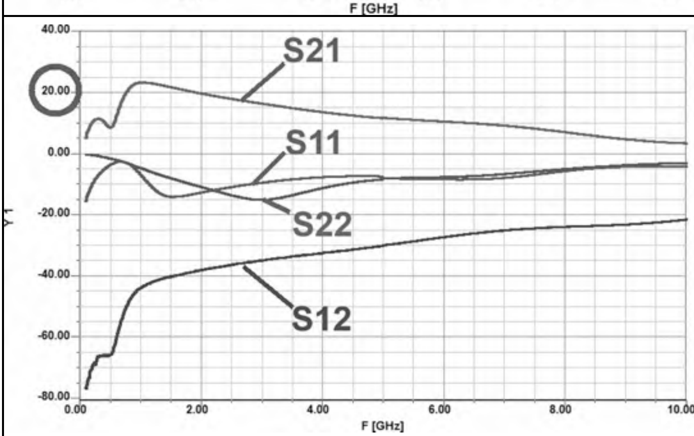

Fig 5: The S parameters look very promising so there is hope.

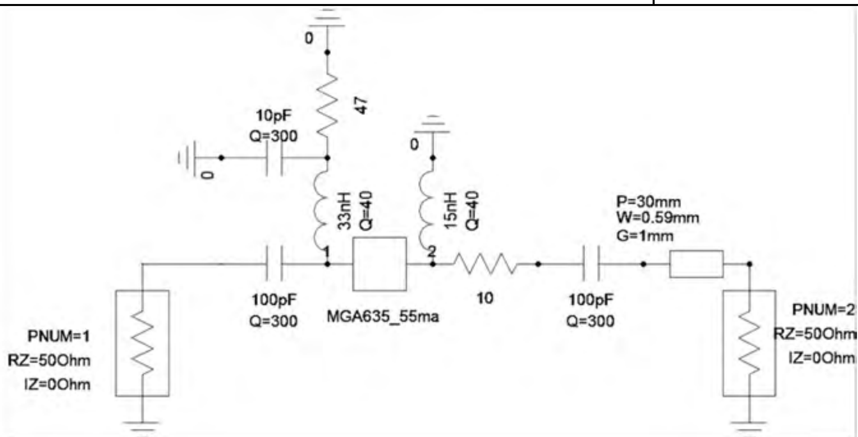

Fig 6: This is the simulation circuit after some work (see text).

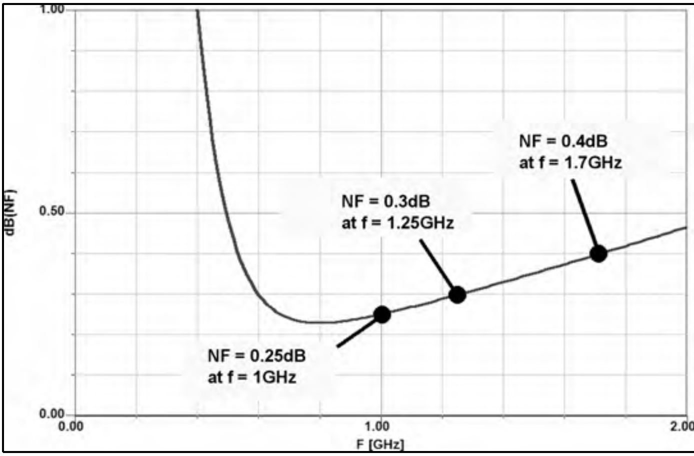

Fig 7: The result of the simulation to control the noise figure is almost a dream.

The stability was investigated up to 10GHz and it is evident that this must be improved (Fig 4). This is only under control up to 8GHz from the simulation.

The S parameters look good - S21 is shown in Fig 5 and it is greater than 20dB between 1GHz and nearly 2GHz.

The circuit was adapted to the frequency range from 1 to 1.7GHz (Fig 6). This was carried out by gradually increasing of the values for L1 and L2 in accordance with the simulation results for the noise figure and permanent control of stability.

The desired value of 0.4dB was achieved with L1 = 33nH / L2 = 15nH and a small additional resistance of 10Ω in the output revealed sufficient stability at 9 to 10GHz (fitted close to the output pin of the MMIC). The amplification, S21, dro-pped a bit as a result but not below the requirement of 20dB at 1.7GHz. The two coupling capacitors C1 and C2 on the input and output were reduced to raise the lower frequency limit. The output microstrip line (more correct: "Grounded Coplanar Waveguide" with a track width of 0.59mm, a gap distance of 1mm on each side and a length of 30mm) could not be missed in the simulation and that resulted in the final simulation diagram. The noise data achieved is shown in Fig

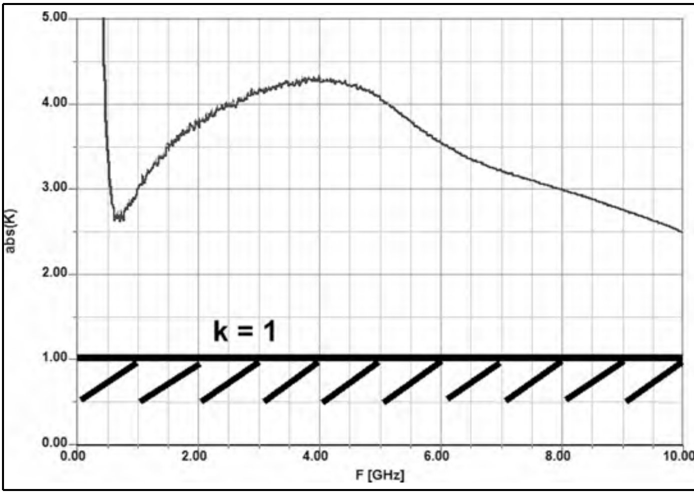

Fig 8: And it looks like the stability factor "k" gives a really stable circuit: significan-tly greater than 1 up to 10GHz.

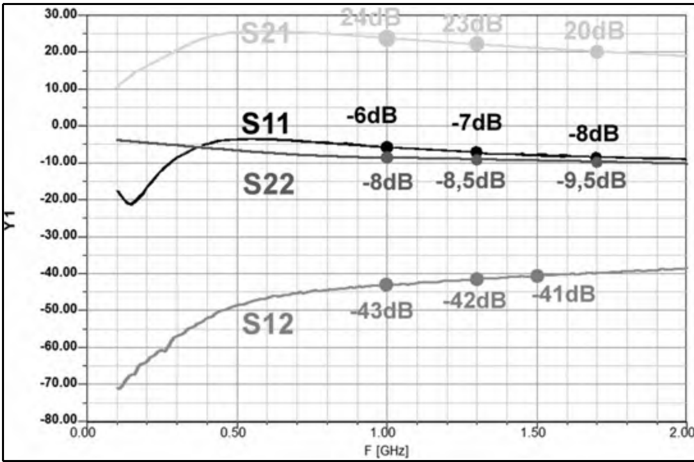

Fig 9: The S parameters have not suffered much due to the changes.

7 as a result of the simulation.

The required stability (k greater than 1 to 10GHz) is now no longer an issue, as shown in Fig 8. The simulated S parameters also give no cause for concern (Fig 9).

The practical circuit has been modified slightly compared to that proposed by Agilent. Fig 10 shows the final version.

The circuit board design could now be done (material: Rogers RO4350B, 35µm copper coated on both sides, board thickness = 10mil = 0.254mm). Overall dimensions are 30mm x 50mm as shown in Fig 11. There is a short microstrip on the left up to the DC isolating capacitor before connecting to the input of the MMIC. The output stripline is 30mm long and both lines are designed as "Grounded Coplanar Waveguides" with a track width of 0.59mm and a gap of 1mm. The line calculator integrated free of charge in the ANSOFT Designer SV software provided these values for Z=50Ω.

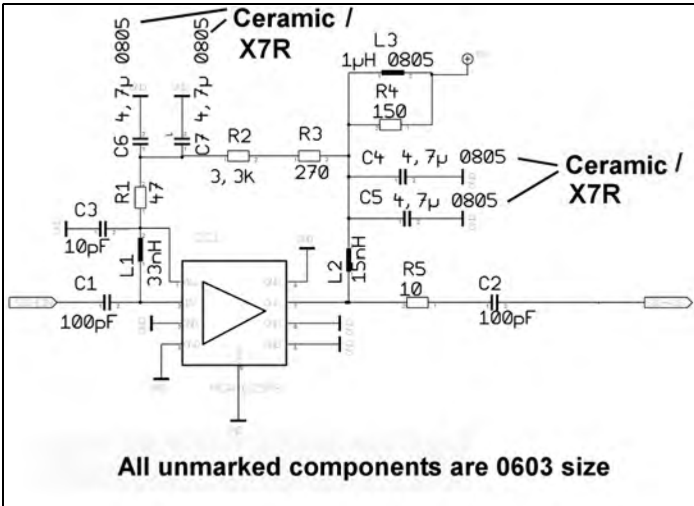

Fig 10: This circuit diagram was developed for the practical circuit.

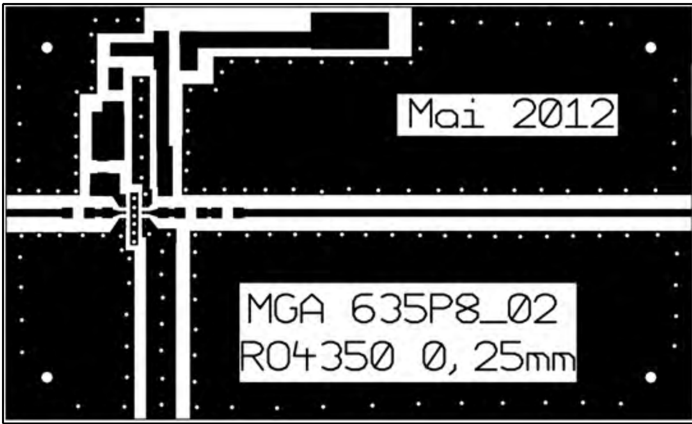

Fig 11: The double sided PCB, size 30mm x 50mm. See text for details.

The central ground connection on the bottom of the MMIC required its own 0.6mm wide ground island with 6 vias that can be seen in Fig 11. All other ground islands on the circuit board have enough carefully separated vias. For those who do not heed these rules with the separate islands including many vias, the circuit will very quickly oscillate. Note: all vias have a diameter of only 0.3mm

3. The prototype

The worry with homemade PCBs is that the silver plated tubular rivets fall out with a low board thickness of 0.25mm. So a professionally manufactured and through hole plated printed circuit board was chosen but that is not exactly cheap.

This only needs a Gerber plot to be created (1 mouse click in the "Target" software) and mailed to the PCB manufacturers then everything else runs by itself. Unfortunately there is the so-called "setup costs" and a minimum order quantity of 4 PCs due to the minimum size of board for the production base load. The people at "Aetzwerk München" [5] were very cooperative; there was even the correct PCB material (RO4350B 0.254mm thickness) in stock. But even the "minimum order" costs (including PCB material) was €235 for 4 PCBs

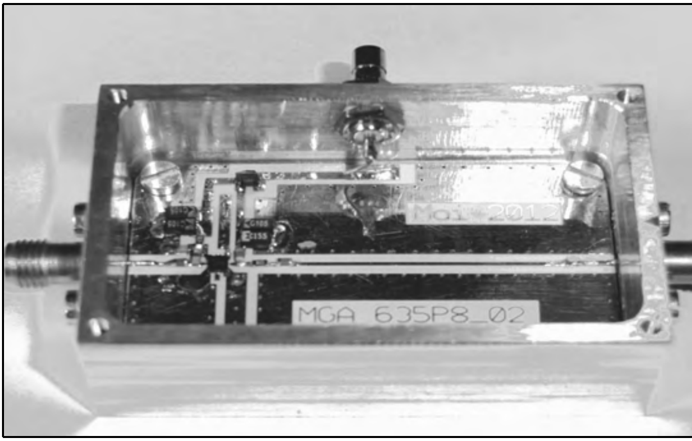

Fig 12: Looking into the finished housing everything is small.

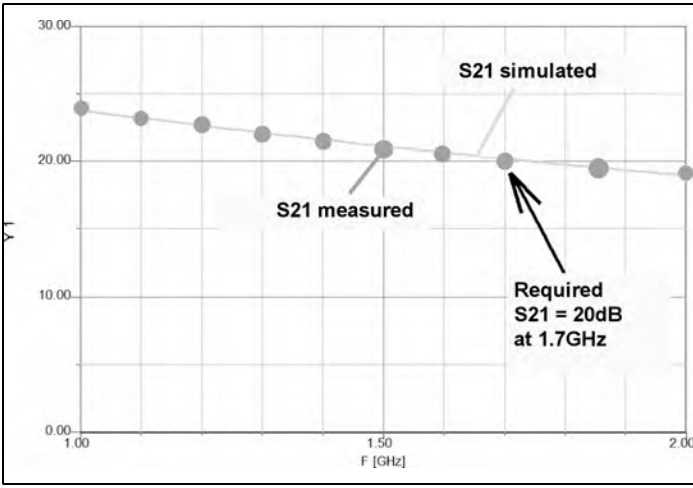

Fig 13: When the S21 theory and practice are the same the story is complete.

A comment on the PCB material: usually for this purpose Rogers "RO4003" is the lowest priced and low loss standard material. But it is not "flame retardant", if there is a fire, what is the advice? It has been given the appropriate additives and is now called "RO4350B". This has changed the electrical data slightly (εr rises slightly, but the losses are higher, at 10GHz: loss tangent lt = 0.0027 for RO4003 and 0.0037 for RO4350. At 2.5GHz however: lt = 0.0021 or 0.0031).

The assembly process is quite slow because of the 0603 size components it needs a steady hand under a stereo microscope or an appropriate microscope (see [4]). Without SMD solder paste in a hypodermic syringe it also takes longer. It has to be attached to the solder in tiny amounts with a sharp scalpel. In addition, a narrow temperature controlled soldering tip 0.8 mm wide is required. The MMIC is only 2mm square with 4 connections on each side with a pin spacing of 0.25mm so the track and pad dimensions are tiny as well.

Fig 12 shows a picture of the unit after successful assembly and fitting into a machined aluminium housing (size = 35 x 55mm). The SMB female connector for

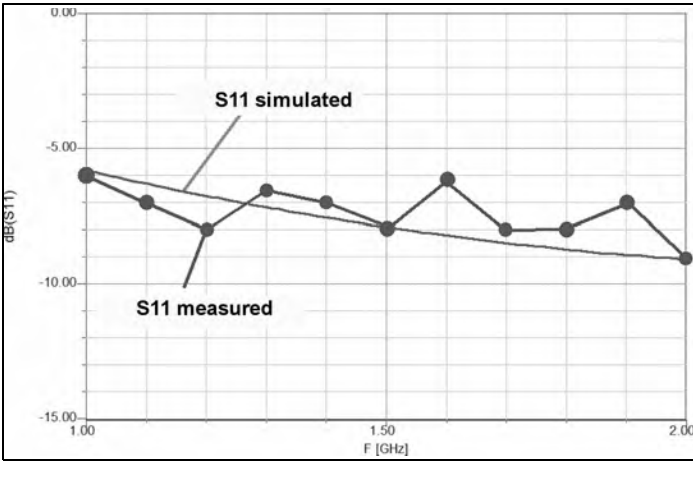

Fig 14: S11 is almost the same as predicted by ANSOFT Designer SV.

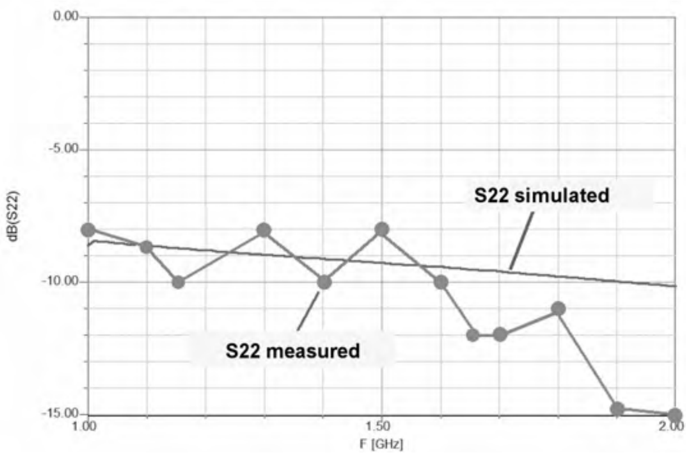

Fig 15: S22 was better than expected from 1.5GHz.

the + 5V supply can be seen at the top of the picture. The input and output signals are special SMA connectors with the centre conductor already flattened (gives the required low reflection transition from the round inner conductor within the socket to the flat microstrip line on the PCB)

An aluminium plate was placed underneath the PCB to lift the now much thinner board, with its microstrip lines, up to the flattened centre conductor of the connectors to give a good and stress free solder joint (Tip: this is absolutely necessary because it is not possible to bend the pin of the socket; this thin pin and the flat flag will break suddenly and quickly).

4.

S parameter measurements to the prototype

The S21 measurement was made with the well known vector analyser (hp8410), the associated S parameter test set (hp87-45A) and a 20dB attenuator connected in front of the input of the test piece to avoid clipping.

The S21 curve can be seen in Fig 13 and it matches the simulation exactly. The S11 measurements meander around the simulation values as shown in Fig 14.

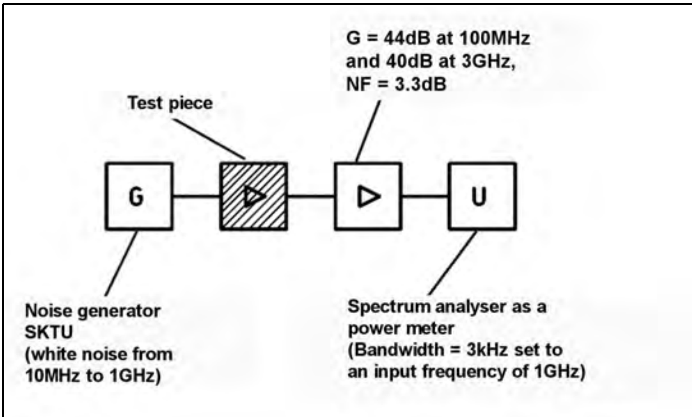

Fig 16: Measuring noise figure using the well known principle of doubling the noise power output.

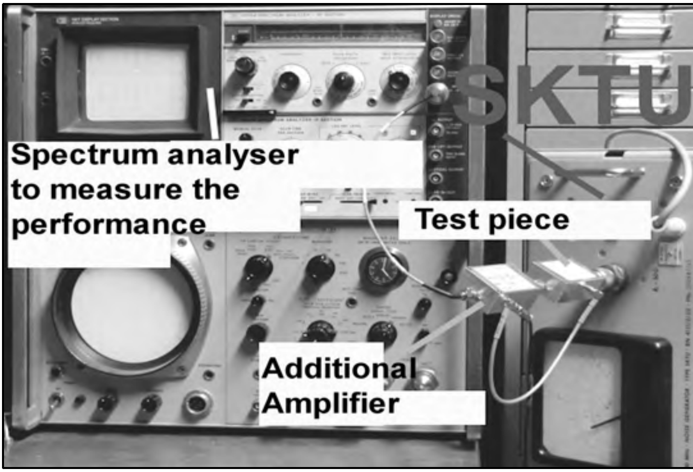

Fig 17: The practical effort to make a measurement according to Fig 16 is however considerable.

S22 matches the simulation up to 1.5GHz but is better than expected (Fig 15). The S12 measurement was more difficult due to the low amplitude. But a value of about -44dB was determined in the range from 1 to 2GHz that is still smaller than the simulation result (between -43dB to -40dB).

5. The noise

With the very small noise figure of 0.4dB maximum expected, it was a very difficult to measure anything at all with the existing local laboratory equipment. Nevertheless, an attempt was made and a suitable setup for the frequency f = 1GHz was put together (Fig 16).

In Fig 17 you can admire what looks like something in practice. The "swept" spectrum analyser is not swept but is set as pure measuring receiver with a bandwidth of 3kHz on the frequency f = 1GHz. Then, output level of the noise generator SKTU was slowly increased until the noise power at the output of the auxiliary amplifier doubled. This corresponds to an increase of the noise displayed on the

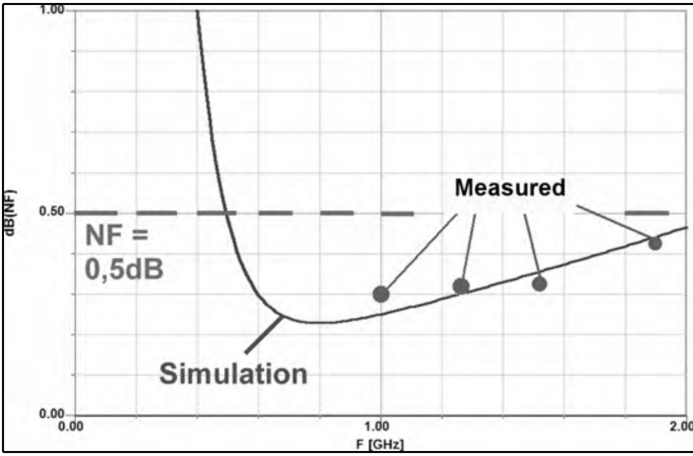

Fig 18: This curve can only be classified as a precious Christmas gift.

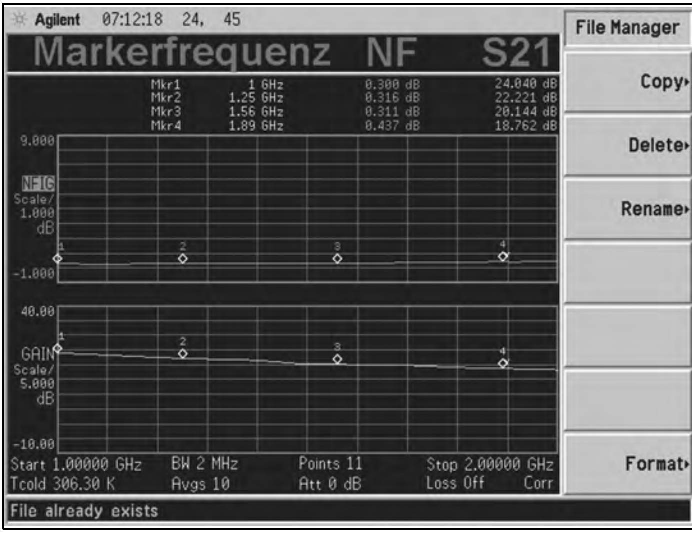

Fig 19: Here is the original picture with the NF and S21 together with markers. So a modern device give a good result.

spectrum analyser of 3dB (or the displayed noise voltage by a factor of 1.41).

Now the residual noise of the amplifier is as big as the performance delivered by the noise channel and the noise figure NF in dB (or the noise factor as a linear ratio) can be read on the display of the noise generator SKTU.

Several measurements showed values of the noise factor somewhere between 1.1 and 1.2. That would be a "noise figure" (NF) for the amplifier between 0.4 and 0.8dB but because of the very low pointer deflection of the SKTU this result can only be considered as indicative. But it is at least the right size (certainly less than 1dB = NF).

The influence of the additional downstream amplifier can be neglected due to the high gain of the device being measured (24dB at 1GHz). The cascaded Noise Figure therefore only shows an increase of 0.02dB.

For more accurate measurements it relies, as always, on help from friends with a modern noise measuring instrument with high resolution and accuracy. One of these friends (Ulli Kafka with his company "Eisch Electronic" in Ulm) gave the author great pleasure with an email containing pictures as well as the classification as "excellent amplifier". This will be immediately understandable if you look at Fig 18: indeed the noise figure up to 1.7GHz remained below 0.4dB and close to the simulation. It only remains to say "Thank God" and thank all contributors.

The original measurement of noise and S21 that provided the good impression was good, especially when you consider the "cold temperature specified" (Tcold) of 306.3K with about +33° Celsius during the measurement as shown in Fig 19.

For the specialist there is an addendum from the data sheet for the MGA635P8 for I = 55mA at 2.5GHz:

- Output IP3 = +35.9dBm
- P1dB_out = +22dBm

If you then start to think about the possibilities of a two stage version for weak Meteosat signals and reception with a patch antenna … there would be enough space on the board...

6. Addendum

A listener of my presentation in Bensheim recently emailed me with an interesting proposal in order to determine these small noise figures with the noise generator SKTU:

"Why don’t you use an attenuator with a precisely known value of 10dB between the generator output and input of the measuring device? Then you will probably need a noise level of 10.5dB delivered by the noise generator to double the output noise power indicated on the screen of the analyser. If you then subtract the 10dB of attenuation from the delivered power level you get the solution = the unknown noise figure (In this case: NF = 10.5dB – 10dB = 0.5dB). I have done this several times in the past with success".

He is right, and this method must be tried. You are always learning.

7. Literature

[1] Data sheet and S parameters files for the MGA635P8 from the homepage of Avago Technologies

[2] Application note from Avago: "MGA635P8 GaAs MMIC ePHEMT 2.5GHz low noise amplifier with superior noise and linearity performance"

[3] Application note from Avago: "MGA635P8 GaAs MMIC ePHEMT 3.5GHz low noise amplifier with superior noise and linearity performance"

[4] Soldering advice for 0.5mm pitch SMD ICs, Bernd Kaa, DG4RBF, VHF Communications Magazine, 4/2011 pp 232 - 236

[5] Etching factory Munich, Germany; PCB manufacturer website: www.aetzwerk.de